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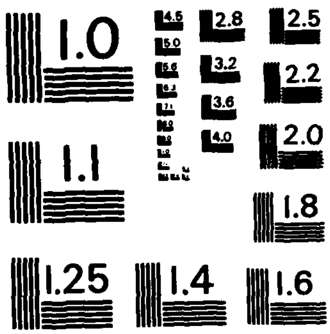

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In this report, we present the results of an experimental investigation of the use of a ferrite loaded cavity for electron beam energy recovery and auto-acceleration. The efficiency in the energy recovery mode is shown to be limited by the formation of virtual cathodes downstream of the energy recovery gap. This limit also is fundamental to autoaccelerator applications. The autoacceleration efficiency is further reduced by a degradation in the beam pulse risetime as a result of the poor high-frequency characteristics of the ferrite cores used.

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FINAL TECHNICAL SCIENTIFIC REPORT

Office of Naval Research Contract #: N00014-83-K-0248

INTRODUCTION:

The research carried out under this contract entitled, "High Current Linear Accelerators," was sponsored during the period February 1, 1983 through 31 January 1985. Funding for this work was actually in place for a shorter period than the nominal contract duration.

The objective of this proposal was to investigate autoacceleration techniques for the development of compact high average electric field electron accelerators. The program utilized ferrite core induction accelerator technology for the coupling of power to and from an intense relativistic electron beam. The experimental investigations and numerical modeling of the experiment were carried out using a 1 MeV, 7 kA, 100 nsec beam. The original objective of this work called for a study of the possible reduction in the amount of the ferrite needed in an accelerator by multiple cycling through the hysteresis loop of the ferromagnetic material. The initial work was designed to produce two such cycles in a single stage post acceleration unit. The results obtained with this system were not encouraging. Autoacceleration efficiencies of order 35 percent and energy recovery efficiencies of 60 percent were obtained.

TECHNICAL REPORT

The body of the technical information developed in this investigation is presented in the preprint of a paper prepared for publication. This paper entitled, "A Ferrite Loaded Autoaccelerator", is appended to

this report together with an earlier document which outlines progress made in the project prior to the Beams '83 meeting in San Francisco.

The experimental investigation carried out utilized the 1 MV, 100 nsec. annular relativistic electron beam. In typical experiments, the beam current was about 7 kA. The use of a carefully designed electron gun led to an extremely cool electron beam. After propagation through the complete system, the minor diameter of the beam was still less than 1 mm. The beam was propagated approximately 50 cm through a homogeneous 10 kGauss axial magnetic field prior to encountering the autoaccelerator gap. In this experiment, the autoaccelerator configuration used a ferrite loaded cavity to couple energy from the beam to an oil filled transmission line, and, after reflection from termination at the end of the line, back to the beam. Diagnostics utilized included voltage and current measurements of the injected beam, the autoaccelerator gap voltage. the transmission line cable current, and X-ray yields in the forward sense, as the beam was brought to rest in a thick copper target. The results obtained from these different diagnostics were consistent to within 10 percent.

As seen in the appended preprint, the system operated qualitatively as expected for the reduction in the beam energy in the initial portion of the pulse followed by an increase in beam energy during the second half of the pulse. The detailed investigation of the operating characteristics of the system showed the performance to be significantly poorer than originally expected. As described in the Appendix, this phenomenon was traced in part to the poor high frequency characteristics of the ferrite. These effects led to an increase in the risetime of the

transmission line current compared to that found in the original beam. A criterion for the efficient autoacceleration of an electron beam is that the risetime of the cable current must be substantially less than the round trip time of an electromagnetic wave along the external transmission line. This phenomenon was the principal cause of the limitation in the efficiency of the autoacceleration process.

A secondary investigation was carried out to assess the capability of the system for energy recovery. Efficient energy recovery could make substantial differences in the efficiency of various electron beam devices, such as free electron lasers operated in the collective regime. In addition to throwing light on this important process, the energy recovery investigation also helps clarify other limitations present in the autoaccelerator configuration. To investigate energy recovery, the external transmission line was terminated in a matched copper sulfate load. Two transmission line impedances, 70 Ω and 96 Ω, were used in this part of the investigation. In the experiments, the best energy recovery efficiency found approached 60 percent. This limit was shown to be due to the formation of virtual cathodes downstream of the autoacceleration gap during the deceleration phase. The maximum efficiency is therefore determined by the limiting current of the decelerated beam. This limitation is also the fundamental limit for the autoaccelerator configuration even when the transmission line risetime is adequately short compared to the transmission line round trip propagation time. We have analyzed the deceleration phase of the electron beam assuming the formation of virtual cathodes limits the performance of the system. The maximum energy recovery efficiencies with high-beam energies and low-

beam currents are shown to reach 80 percent for interesting beam currents. Physically, we find that if the beam current is too large,(i.e. it exceeds the beam limiting current after the deceleration in the autoacceleration gap), that this information is communicated back to the injector and the beam current pulse is badly degraded as shown in the appended report. Satisfactory agreement was obtained between the calculated performance of the system using the virtual cathode hypothesis and experiment. The reduction in overall system efficiency in the autoaccelerator configuration between the 60 percent energy recovery and 35 percent efficiency in the autoaccelerator mode was set by risetime limitations in the ferrite.

CONCLUSIONS:

We have demonstrated in this program that the energy associated with an intense relativistic electron beam may be recovered with efficiencies approaching 80 percent. The use of ferrite cores produces a further limitation in the autoaccelerator performance by degrading the risetime of the external transmission line pulse.

APPENDIX

A FERRITE LOADED AUTOACCELERATOR

BY

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ABSTRACT

An account is presented of the performance of an autoaccelerator in which energy is extracted from the front portion of a relativistic electron beam, via a ferrite loaded cavity, and stored in an oil filled transmission line. The extracted energy is returned to augment the energy of the electrons in the latter half of the beam. Peak efficiencies of 33% are reported. The device was also used to investigate beam energy recovery. In this application the line was terminated in a matched load and up to 60 % of the beam energy recovered. The autoaccelerator performance was limited by current pulse rise time degradation in the ferrite and by the formation of virtual cathodes during the deceleration phase. The latter process also limits the energy recovery.

Introduction.

A number of workers (1,2) have explored the use of autoacceleration for increasing the energy of electron beams at the cost of a reduction in the pulse duration. Most of the work carried out has been at the sub megavolt level, although Friedman has recently reported increasing the energy in an electron beam from 4.2 to 7.4 MeV.(3) In these experiments

the autoacceleration has been in a co-linear configuration where the gain of the system is limited to unity. Variants on this geometry, which use two coaxial beams can have gains greater than one. These geometries, of which the wake field accelerator (4) is typical, frequently use radial pulse lines with one annular beam at the outer edge of the system and a lower current pencil beam on axis. Gains of greater than one may also be obtained in co-linear configurations by the rapid switching of slow rise time beams (5).

In this paper we present an account of a co-linear system in which the coupling to the external transmission line is through a ferrite core surrounding the electron beam. We have explored the system operation in a variety of configurations including:

1. Varying the ratio of the beam to the transmission line impedance,
2. Varying transmission line terminations and,
3. Different transmission line lengths.

The object of the experiments was to define the limits of operation of the system both in the autoaccelerator and energy recovery modes, (6.7) and to determine the physical processes which limit the efficiency.

Experimental Configuration

The experimental arrangement used in this investigation is shown in Figure 1. It consists of a foilless diode which was used to generate a 4.0 cm diameter, 0.1cm thick, 700-1000kV, 6-8 kA electron beam. The drift tube diameter was 6.7 cm. The tube diameter downstream of the autoaccelerator gap was 1.2cm smaller than the upstream diameter so that the applied 10 kGauss axial magnetic field provided some magnetic

insulation between the drift tube walls on either side of the post acceleration gap. Nine TDK P-14 ferrite cores, which allowed a flux swing of 0.025 V.sec., were used to couple the beam energy to the transmission line and vice-versa. The oil filled transmission line had either a 70 or a 96 Ohm impedance. Lengths appropriate to round trip signal propagation times of 17, 22,28, and 35 nsec. were used. In some experiments the load at the end of the transmission line included a self breaking gas switch which was used to decrease the rise time of the transmission line pulse.

Diagnostics used included voltage monitors to determine the beam injection energy and the voltage swing across the autoaccelerator gap, Rogowski coils to measure the beam and the external transmission line currents, and an X-ray scintillator photodiode to give a time resolved picture of the X-ray yield in the forward sense produced by dumping the electrons into a thick copper or steel target. The various monitors were calibrated against each other and agreed to within $\pm$ 10 %.

Experimental Results

Figure 2 shows representative waveforms for the autoaccelerator using the 70 Ohm transmission line with a short circuit termination and a 28 nsec. round trip length transmission line. The dashed line shown on the X-ray detector output represents the signal obtained when the autoaccelerator gap was shorted. The signals are not time synchronized. The gap spacing was selected by comparing the x ray yield when the beam was dumped into a target upstream of the gap with that found when the target was located downstream of the gap. For gaps of less than 5 cm the two signals were identical when a short circuit was placed across

the gap. The output beam energy is determined from the sum of the injection and the autoaccelerator gap voltages and is indicated in the last part of the figure. The maximum increase in the beam energy in any of the cases investigated was 33%. Several features of the signals are distinctive; for example, the transmission line current exceeds the injected current as would be expected for a short circuit load on the transmission line. The decrease in the X-ray yield in the early part of the pulse, compared to that found with no post acceleration, indicates that the beam energy has been decreased as a result of the transfer of beam energy to the transmission line. The enhancement in the x ray signal during the second half of the pulse shows the increase in beam energy as the stored energy is fed back to the beam. Experiments of this type were carried out with load impedances of 0, 35, 70 Ohms, and using the four transmission line lengths indicated earlier. The results could be modelled well using simple transmission line theory with two additional assumptions; firstly there is an attenuation of 10% in the wave amplitude in making a round trip through the system, and secondly that the actual round trip time for a pulse through the system is 17.5 $\pm$ 2.5 nsec. longer than calculated for the ideal line.

Based on these results and the modelling calculations we added a self breaking gas switch in parallel with a matched load to the end of the transmission line. The self breaking gas switch was used to control the time of the reflected pulse and to reduce its rise time to 5 nsec. The reduced rise time should result in an increase in the autoaccelerator efficiency. As seen in figure 3 the decrease in the return pulse risetime is apparent in the transmission line current waveform. The

timing of the return pulse is closely controlled by the pressure in the gas switch at the end of the transmission line. Although the system operated as designed, there was no increase in the electron beam energy over and above that reported prior to the change. The reason for this apparently lies with the degradation of the pulse rise time due to the frequency dependence of the properties of the ferrite cores. The resistivity, for example, begins to increase significantly at a frequency of 10 MHz so that larger losses should be expected as the rise time drops below about 25 nsec. (8)

In the experiments described to date the system was operated at currents well below the vacuum limiting current in the upstream drift tube. Attempts to increase the current lead to violent fluctuations in the measured drift tube current. An increase in the transmission line impedance to 96 Ohms showed similar fluctuations with the beam current at the 6 kA level. Figure 4 shows the beam current observed in this condition. The current drops to a very low value during the main pulse. Shorting of the autoaccelerator gap at the grading rings restored the current to its normal magnitude and shape. A reduction in the beam current lead to stable operation although the transmission line current was smaller than the beam current until it was decreased to about 4.5 kA. These results, which were obtained with a matched load at the end of the transmission line, show that a portion of the electrons were reflected at, or downstream of, the autoacceleration gap. In these cases damage patterns showed, that downstream of the gap, the beam thickness had increased to about 0.5cm., a 500% increase in the beam transverse dimensions. The absence of a reflected wave on the transmis-

sion line confirmed that the limitation occurs during the electron deceleration phase. The maximum energy recovery efficiency from the beam into matched load was 56%. Friedman reports in simulation work recovery efficiencies of up to 80%. (6) The efficiency should increase with increasing beam energy as discussed in the following section.

Discussion of Results

The results reported in the previous section have been partially discussed above. In this section we report results showing the simulation of the waveforms obtained using the diode voltage and beam current waveforms as inputs. The system is modelled assuming ideal coupling between the beam and the transmission line. We calculate the transmission line and autoaccelerator gap waveforms for all times, including multiple reflections from the line termination. The beam is treated as a current source and causes a voltage doubling at the autoaccelerator end of the transmission line. This boundary condition leads to the simple criterion that the transmission line current should exceed half the the instantaneous beam current for energy transfer from the line to the beam. This implies that the beam current rise time must be short compared to the wave round trip time on the transmission line for efficient autoacceleration. The X-ray signal was calculated using the model assuming that the forward scattering intensity of the X-ray signal scales as $IV^{2.8}$ and the absolute values of the intensity were determined by comparison with the X-ray emission in the absence of autoacceleration. Figure 5 shows a quantitative comparison between the experimental x ray and cable current outputs and the simulated values. As stated earlier the agreement results if one uses a pulse round trip time on the cable

which is 17.5 nsec greater than that calculated and also include a 10% energy loss per round trip on the cable. Physically it seems likely that the latter is due to losses in the ferrite cores. The increase in the propagation time of the wave through the transmission line system was shown to be constant and independent of the actual transmission line length and hence is also probably associated with the ferrite. Diffusion in the core leads to a minimum rise time of approximately 10 nsec. (9). The characteristic time for electromagnetic wave propagation through the ferrite cores is comparable to the diffusion time so that the two effects combine to yield a pulse with a reduced rise time and a delay.

The experimental results suggest that the operation of the autoaccelerator is limited by the beam conditions downstream of the postacceleration gap during the deceleration phase. We now examine this in more detail. Referring to figure 1 we denote the beam and drift tube radii downstream of the autoaccelerator gap by the symbols a and b respectively. The corresponding radii upstream of the gap are a and b respectively. (Experimentally a=a') In this notation the voltage measured across the autoaccelerator gap is $v_{bb'}$. The beam injection energy is γ_{inj}, the current I, and the transmission line impedance Z_o. Since the flux is concentrated in the ferrite cores we can set $\oint E.dl=0$ for a path along the beam, radially out to the drift tube wall, across the autoaccelerator gap, and back to the diode along the conducting wall. This gives

$$(\gamma_{inj} - \gamma_D')mc^2 = e(V_{bb'} + V_{ba}) \qquad (1)$$

where

with a one kiloampere unneutralized proton beam entering the drift tube along the axial guide field, shows that the surface field at the drift tube walls would be less than 100 kV/cm. This is marginal for the emission of the electrons required to neutralize the space charge of the proton beam. It seems that it is probably important to form a well-defined virtual cathode surface capable of providing all of the electrons required to neutralize the proton beam space charge. It would also seem desirable to increase the proton current density so as to ensure beam neutralization from the walls of the system. Failure of both of these processes would necessitate the use of an externally driven source of electrons for beam neutralization. We are presently in the process of testing the new geometry at higher voltage and at greater current densities to establish the prospect for good beam transport without the addition of externally driven ion neutralization sources. The role of asymmetries in the diode fields is also being studied.

Autoaccelerator Research

Autoacceleration of high current electron beams has been investigated in a number of laboratories [6,7]. In this investigation we describe research carried out into the use of passive ferrite loaded induction accelerator systems for the acceleration and pulse shaping of electron beams. An advantage of the ferrite loaded autoaccelerator over those using coaxial vacuum cavities is that the flux is concentrated in the ferrite, hence it is possible to produce uniform acceleration fields on the charged particles, independent of their radial location in the accelerating gaps. It is also possible to make compact systems, and to readily change the parameters of the system, e.g., the electrical length or the impedance of the transmission line used for coupling the energy to and from the beam.

The autoaccelerator system used in this work is sketched in Fig. 2. It consists of an oil insulated, ferrite loaded, cavity containing either 6 or 9 TDK P14 ferrite cores. The cores are driven from their remnant magnetization state to saturation in the reverse sense by the field associated with the current in the beam-return conductor circuit. A secondary circuit links the cores, coupling a fraction of the beam power to a 70 ohm oil filled transmission line. A variety of transmission line lengths have been used, having electrical lengths corresponding to pulse round trip times ranging from 17 to 35 nsec. Most of the work described here were carried out with a nominal 28 nsec round trip time cable. The ferrite used had a flux swing of 0.025 Vsec. A 5-6 kA, 800-900 kV annular electron beam was generated in the diode. The diode configuration employed produced a 4.0 major diameter, 0.1 cm minor diameter electron beam. The beam propagation was controlled by a strong axial magnetic field. The parameters used in this initial study were chosen so that the beam was at all times far from the limiting current of approximately 18 kA in the short first section of drift tube. The diagnostics employed in the experiments included measurements of the:

(i) Beam injection energy and current,

(ii) Time resolved thick target x-ray yield in the forward direction,

(iii) Transmission line current and,

(iv) The autoaccelerator gap voltage.

Figure 3 shows data typical of the results found for this system. Representative oscilloscope traces showing the autoaccelerator gap voltage, the transmission line current, and the x-ray monitor output are shown in the figure for three sets of conditions corresponding, from left to right to:

(i) The autoaccelerator gap shorted at the grading rings. In this condition we only have an x-ray output pulse. The accelerator gap spacing of 5 cm was set to maintain the same x-ray signal with the target in front of and behind the gap.

(ii) The beam energy was coupled through the ferrite to the transmission line, which in turn was terminated in a resistive load of approximately 40 ohms.

(iii) The configuration is identical to that used in (ii) with the exception that the transmission line is terminated in a short circuit. Immediately below these records are traces illustrating the injected beam current and voltage.

In the resistive load case we observe that the transmission line current of about 6 kA is somewhat greater than the measured beam current, as a result of the load impedance being smaller than the characteristic impedance of the cable. The x-ray monitor shows a substantial decrease in amplitude reflecting the loss of beam energy. The increase in the x-ray signal amplitude towards the end of the pulse is associated with reflection of the wave from the load at the end of the line. Based on the measured beam and transmission line parameters we find that we have in this case recovered one-quarter of the beam energy into the load at the end of the line. With a matched load we have demonstrated recovery of more than half

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Particle Beams, Sept. 12-14, 1983, San Francisco, CA

GENERATION AND CONTROL OF CHARGED PARTICLE BEAMS USING INDUCTION ACCELERATORS

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Abstract

Investigations have been carried out into the use of Induction Linacs for the acceleration of proton beams. A 1.5 MeV, 2 kA, 50 nsec beam has been generated using an inductively fed magnetically insulated diode. Results will be reported on propagation with and without collective focusing of the beam.

A program to study autoacceleration techniques for the production and time compression of high energy beams has been started recently. A ferrite loaded cavity was used to couple energy from the beam to a 70 ohm transmission line and, after a predetermined delay, back to the beam. Initial experimental results demonstrating particle acceleration and pulse compression will be presented.

Introduction

The Induction Linac accelerator research program at Cornell University has two main elements:
(i) A study of the physics of a high current proton induction linac and,
(ii) An investigation of techniques for the temporal modulation of the beam energy and current.
The first problem under investigation is the efficient generation of a multikiloampere, megavolt proton beam in a magnetically insulated diode, and its transport over length scales commensurate with the employment of a multi-cavity accelerator.

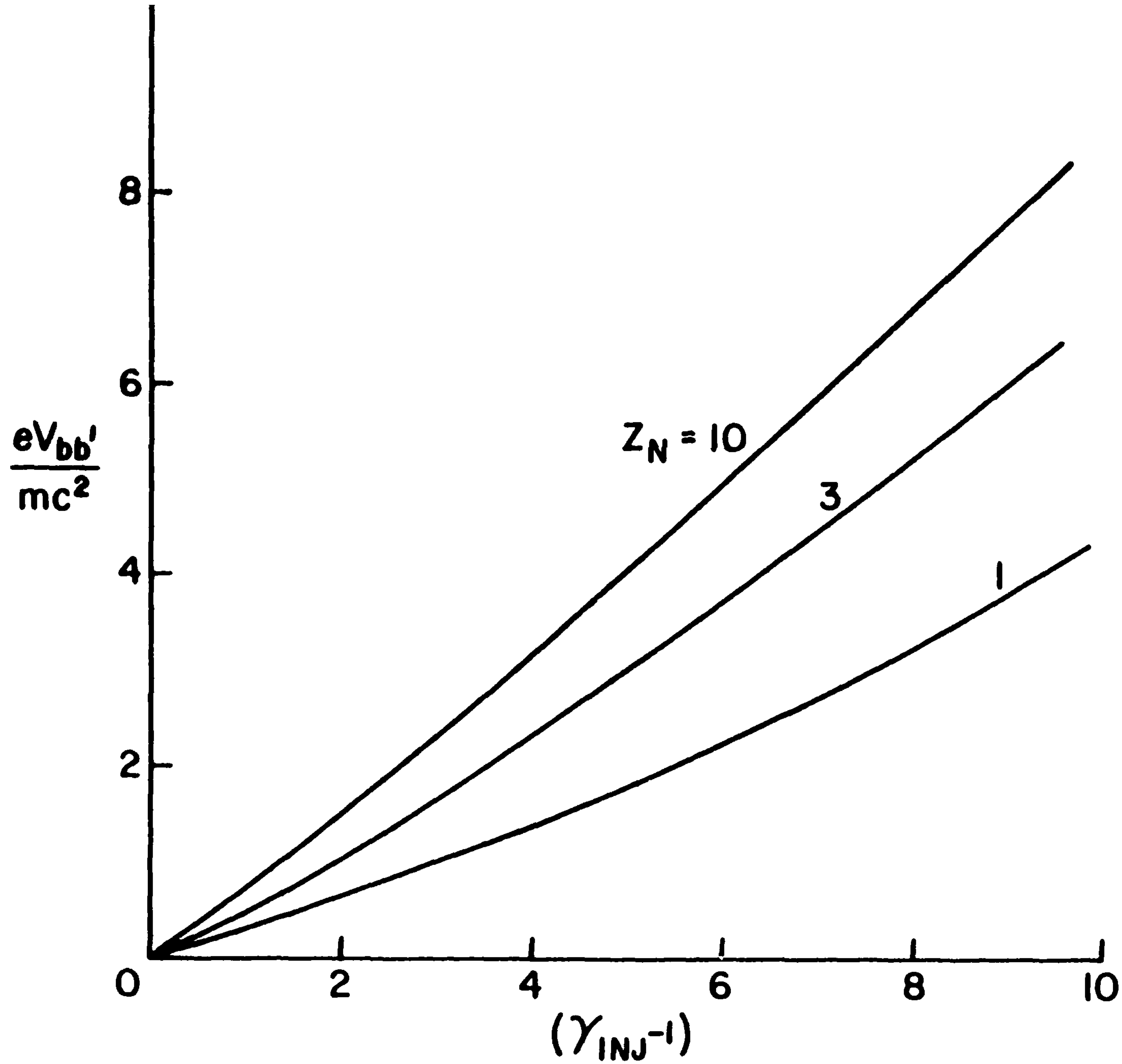
The second aspect of our investigation deals with the autoacceleration of an electron beam in transport through a ferrite loaded induction accelerator cavity. The beam return current loops the ferrite cores, and hence couples power from the beam to a short length of transmission line. The system has been used in two different modes. We have demonstrated the recovery of beam energy by coupling the beam power through the ferrite and transmission line to a passive load at the end of the line. In addition we have made first meaurements of autoacceleration of the electrons in the system by terminating the transmission line in a short circuit. The energy recovery mode is of considerable interest as it provides a practical demonstration of a way to increase the efficiency of a number of collective devices such as the free electron laser.

In the following sections we shall report experimental results obtained with both devices.

Proton Induction Linac Research

We have recently reported progress in this area and will only present a very brief update of this investigation [1]. Figure 1 shows two of the configurations used in the study. The upper part of the figure illustrates the geometry successfully used for the efficient magnetic insulation of the induction linac diode [2]. This configuration was found to produce proton beams with a very high efficiency (an ion to total diode current of order of 75%); the transport of the beams was however poor. We have recently tested a series of diode and transport field geometries, the most recent of which is shown in the lower part of the figure. The main feature of this system is the rapid transition from a magnetically insulating diode to a homogeneous axial guide field suitable for the collective focusing [3,4], and hence efficient transport of the beam. We have found that it is important to minimize the radial return magnetic field crossed by the beam after extraction from the diode. Experimental observations made, using carbon activation techniques, show an increase in the beam transport efficiency when the beam does not have to cross magnetic field lines. Similar results have been found in other studies at Cornell where the effect of the return field on the beam scattering angle of the protons has been measured, and found to increase rapidly in propagation through the return field region [5].

To date we have used the new geometry in a series of low energy ($\lesssim$700 keV) tests. The magnetic insulation has been found to work satisfactorily although at a significantly lower ratio of ion beam current to total current than that found earlier for the upper field geometry system. Measurements at the exit plane of the diode indicated that the ion current distribution, at the one kiloampere current level, had substantial (~3:1) azimuthal asymmetries which varied in both magnitude and location on a shot-to-shot basis. The data suggested that both the anode turn on and the beam neutralization were marginal at the operational levels. The less satisfactory operation may be associated with a greater degree of asymmetry in the diode magnetic insulation field than that found in the original geometry of Fig. 1a. A calculation of the radial electric field associated



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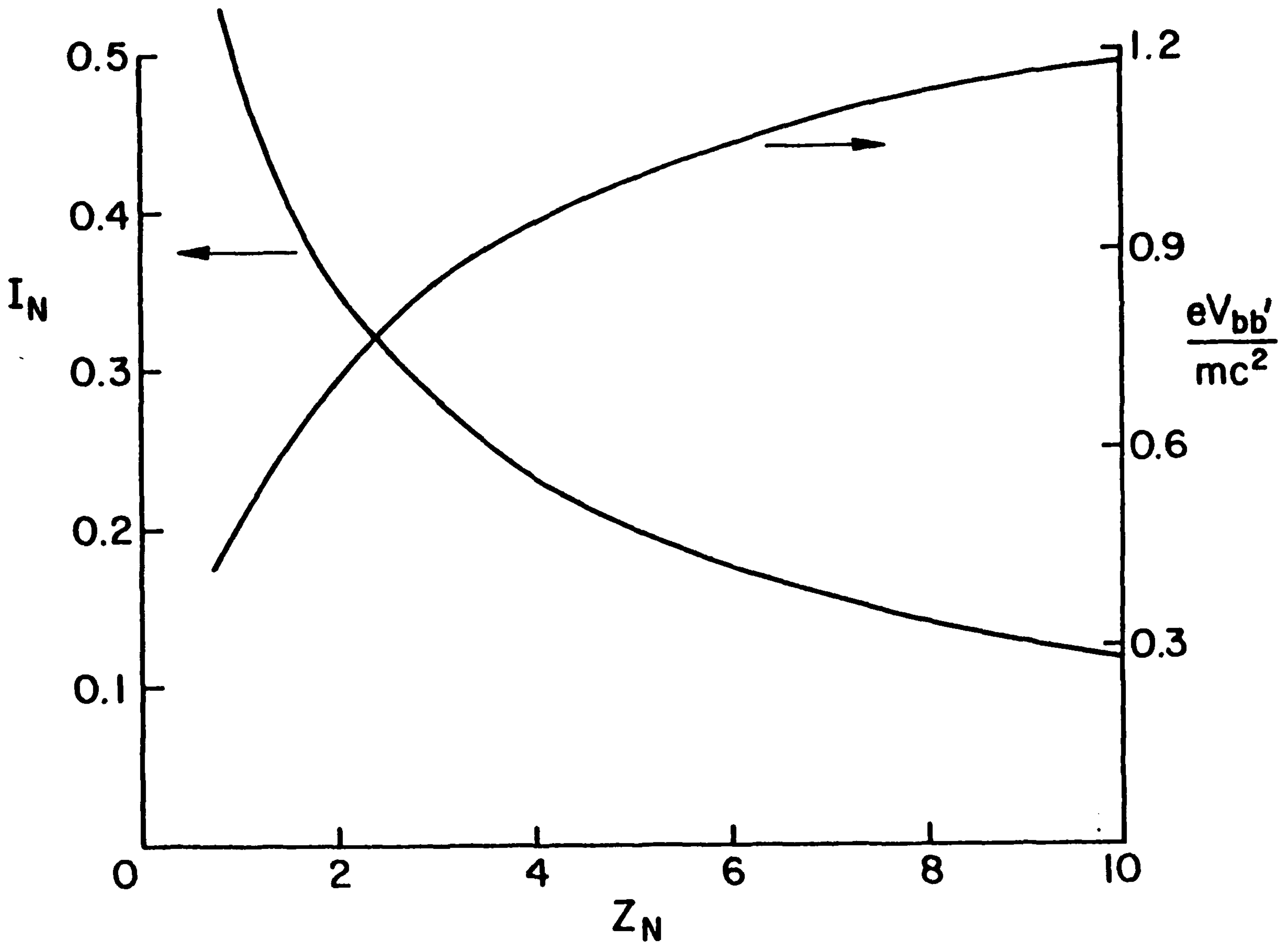

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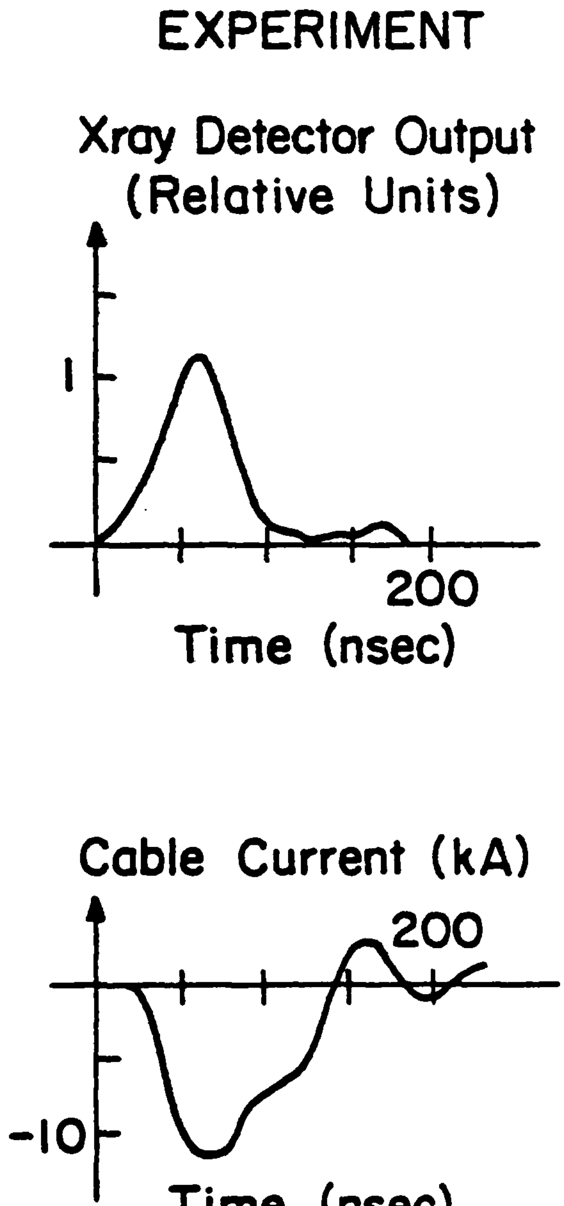
EXPERIMENT
SIMULATION
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Time (nsec)
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200
Cable Current (kA)
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Time (nsec)
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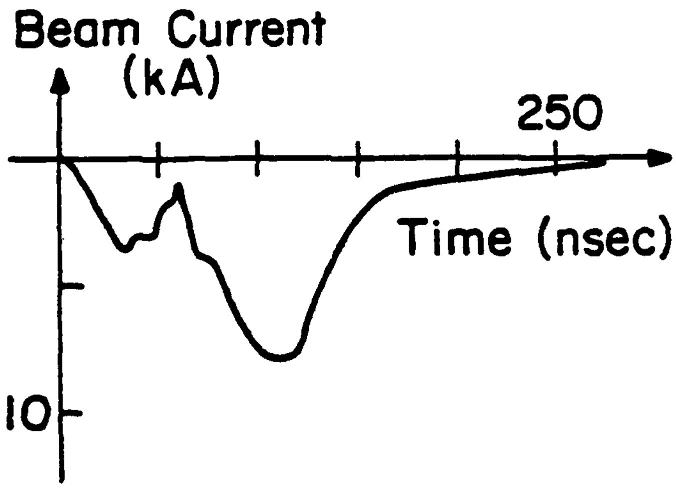
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Time (nsec)
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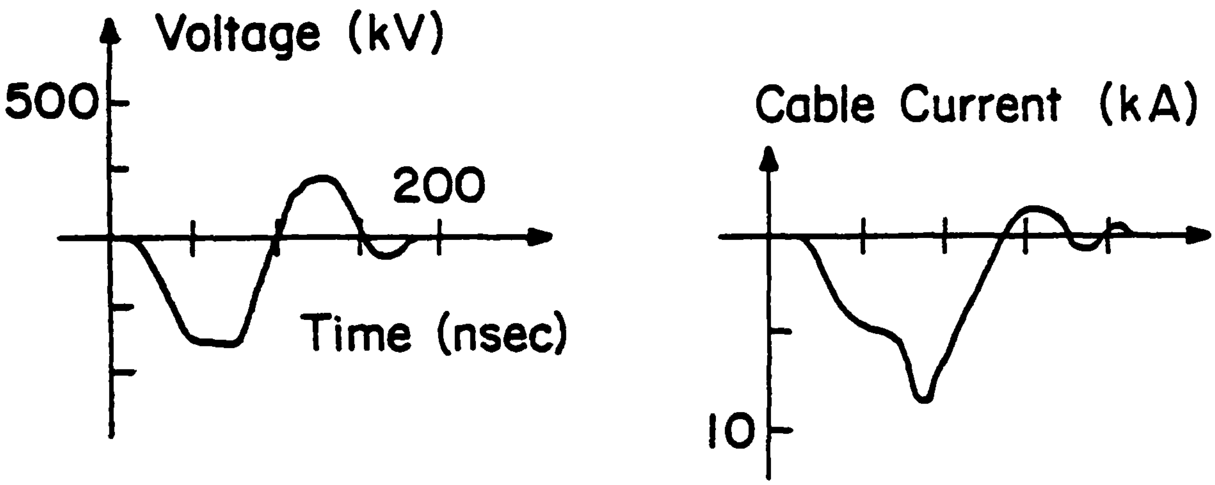
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Cable Current (kA)
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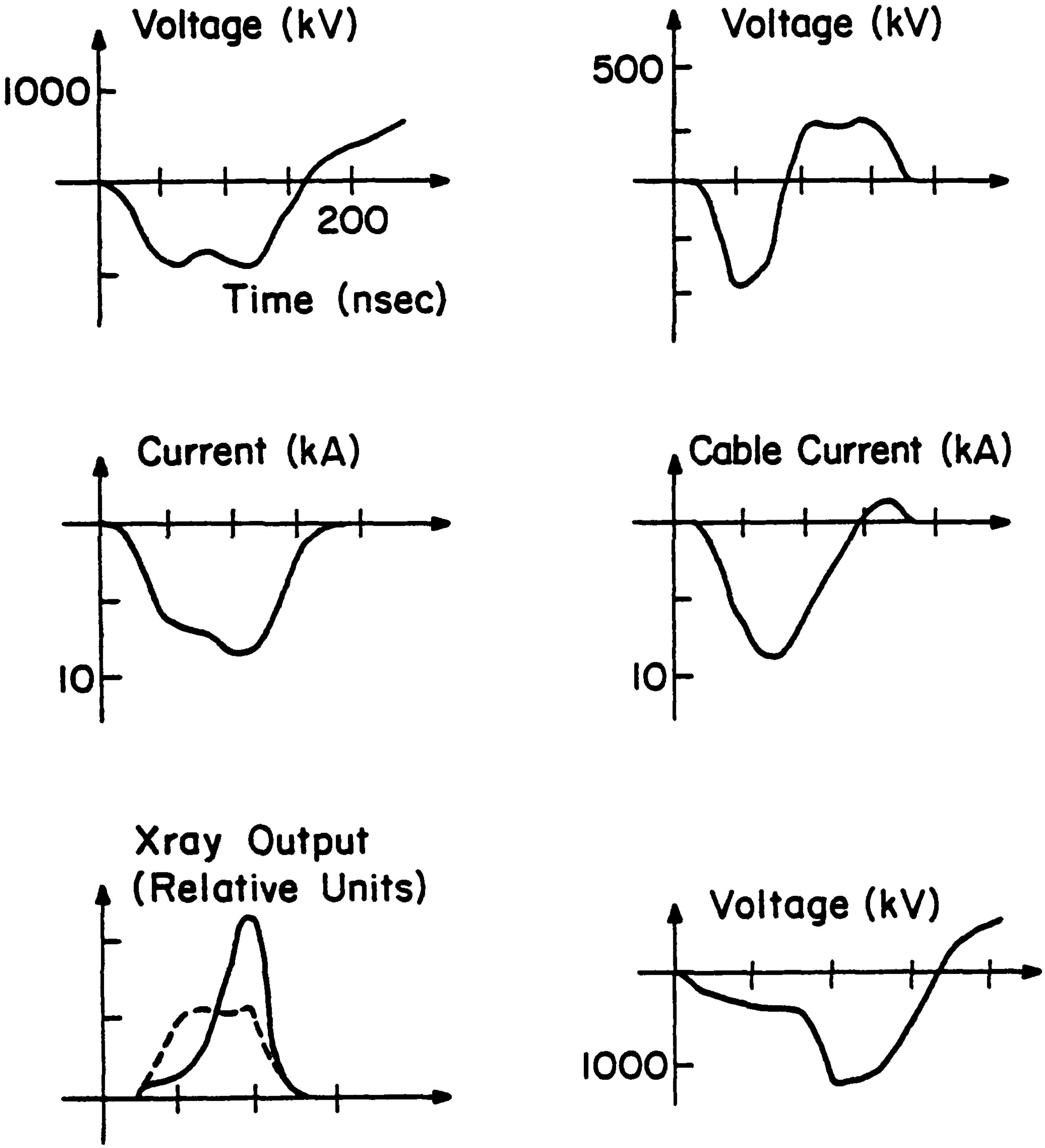
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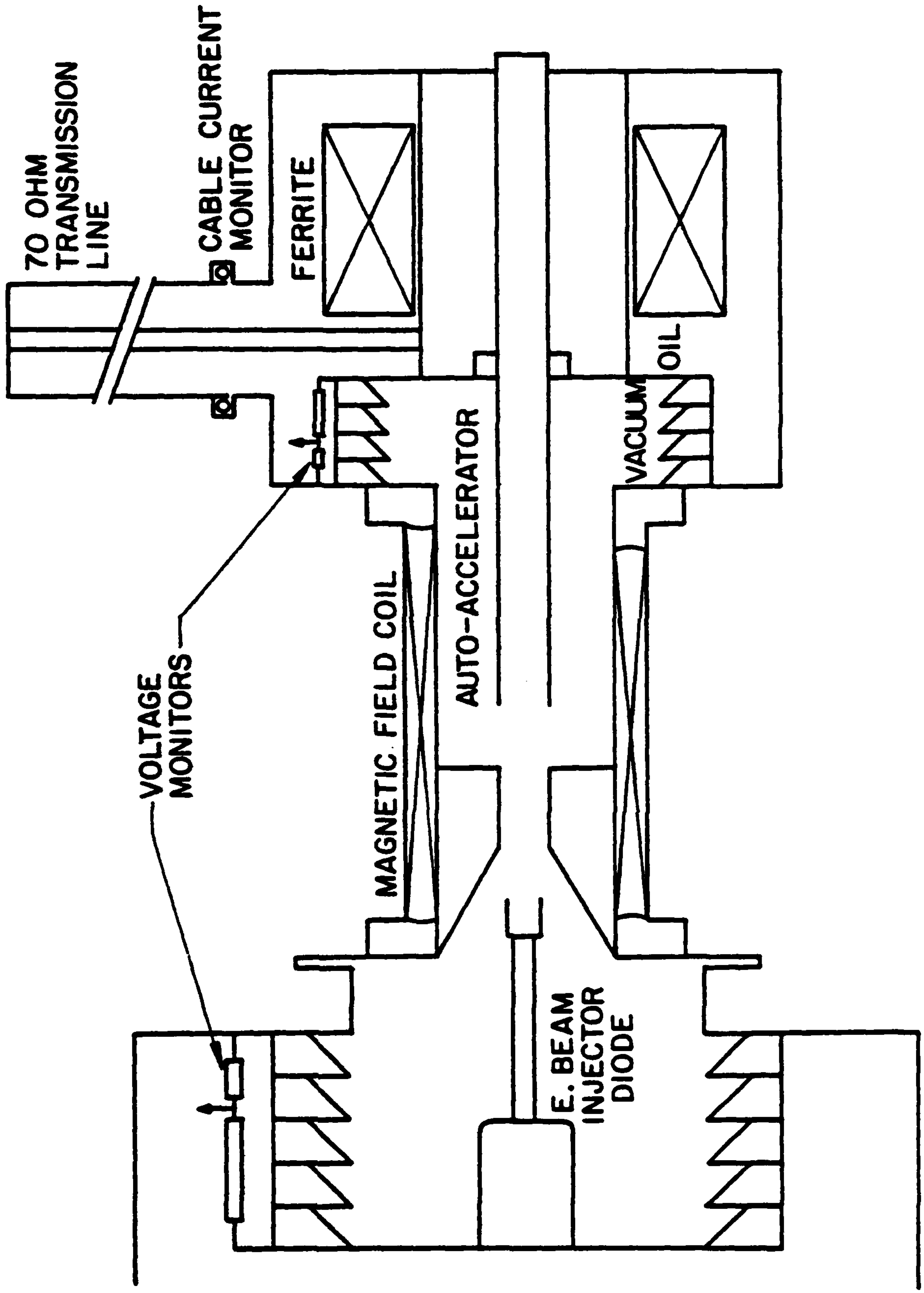
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MONITOR
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VACUUM
AUTO-ACCELERATOR
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VOLTAGE
MONITORS
E. BEAM
INJECTOR
DIODE

FIGURE CAPTIONS

1. Experimental arrangement.

2. Typical experimental waveforms. Starting upper left and rotating counterclockwise: 1) Diode voltage, 2) Beam current, 3. Forward X-ray output from thick target. (The dashed line shows the output in the absence of autoacceleration, 4) Computed beam energy after the autoacceleration (= 1+6), 5) Transmission line cable current, 6) Autoaccelerator gap voltage.

3. Autoaccelerator gap voltage and transmission line current with gas switch installed at the end of the line. Note the sharp increase in the cable current following switch closure.

4. Typical beam current obtained when the downstream current exceeds the vacuum limiting current.

5. Experimental and calculated X-ray output and cable current showing agreement of modelling with experiment.

6. Calculated maximum current and autoaccelerator gap voltage achievable for a 70 Ω cable and an 800 keV electron beam.

7. Calculated autoaccelerator voltage versus beam injection kinetic energy (in units of mc^2) for several values of cable impedance.

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[8] Unpublished (T. D. K. internal memorandum).

[9] G. W. Still, M.S. Thesis, Cornell University (1985).

1 MeV this figure is close to 70% in the best case. The efficiency improves as the current to limiting current ratio decreases.

CONCLUSIONS

The use of ferrite cores in co-linear auto-accelerator configurations is limited by rise time effects. Pulse rise times of less than 10 nsec. cannot be obtained due to the non-ideal characteristics of the ferrite.

The performance of the auto-accelerator as an energy recovery device appears to be limited by the formation of a virtual cathode in the deceleration phase. The numerical value of the efficiency is greater for low current-beams and high impedance transmission lines. At 1 MeV the efficiency for beams of interest is probably limited to a value of order 70%. The efficiency increases with increasing beam energy.

The auto-accelerator efficiency has an absolute limit set by the considerations listed in the previous paragraph. This limit will be reduced as the ratio of the beam current rise time to the transmission line transit time increases.

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This result is expected since the vacuum limiting current in the downstream tube should not depend on whether V_{bb}, is a voltage source on the voltage due to a current source (with a current equal to the beam current.) The results of this analysis are shown in figure 6 for an 800kV beam as a function of the normalized impedance. The experimental conditions correspond to Z_N = 3.67 or 5.03 for the 70 and 96 Ohm transmission lines. The maximum beam current and autoaccelerator voltage are

	Calculation		Experiment
Transmission Line Impedance	Beam Current	Autoaccelerator Voltage	Autoaccelerator Voltage
70 Ohms	6.7kA	469kV	420kV
96 Ohms	5.4kA	516kV	432kV

These results are in good agreement with the experiment. The energy recovery efficiency increases at small beam currents with high impedance transmission lines. For multikiloampere beams at energies approaching 1 MeV the maximum energy recovery efficiency in a single beam is of order 60%. Similar efficiencies should be obtainable in the auto-accelerator configuration if the transmission line pulse rise time is short enough. Rise time limitations in the ferrite cores reduce the efficiency in the experiments. Finally we show in figure 7 the gap voltage as a function of the beam injection energy for the case Z_N = 1, 3, and 10. The ratio of value of the ordinate to that of the abscissa is a direct measure of the achievable energy recovery efficiency. For a 4.5 MeV beam it is possible to obtain a greater than 80% energy recovery with Z_N = 10. At

$$V_{b'a'} = \frac{I}{2\pi\epsilon_0 \beta_D' c} \ln\left(\frac{b'}{a'}\right). \tag{2}$$

In these equations γ_D' and β_D' are the usual relativistic factors applied to the electron drift energy and normalized velocity. These equations are readily rewritten to express the current as a function of γ_{inj} and γ_D'. The current is equal to

$$I_N = \frac{(\gamma_{inj} - \gamma_D')\beta_D'}{1 + \beta_D' Z_n} \tag{3}$$

and is a maximum when

$$\gamma_{inj} = (\gamma_D')^3 + Z_n[(\gamma_D')^2 - 1]^{3/2} \tag{4}$$

In these equations we have normalized the current and impedance using

$$I_N = I\left[\frac{e \ln(b'/a')}{2\pi\epsilon_0 mc^3}\right] \quad \text{and} \quad Z_N = Z_0\left[\frac{2\pi\epsilon_0 c}{\ln(b'/a')}\right] \tag{5}$$

Equations 3 & 4 may be combined to yield the normalized limiting current I_m

$$\gamma_{inj} = (1 + I_m^{2/3})^{3/2} + Z_N I_M \tag{6}$$

which reduces in the limit $Z_N = 0$ to the usual limiting current relationship. It is of interest to note that we can define an injection gamma γ_{inj}'

$$\gamma_{inj}' = \gamma_{inj} - Z_N I_N$$

such that

$$(I_N)_{max} = [(\gamma_{inj}')^{2/3} - 1]^{3/2}$$

of the beam energy. It should be noted that these figures for the energy recovery do not indicate limits on efficiency. We expect to operate at much greater efficiency as the current is increased towards the limiting value, or as the line impedance is increased at fixed beam current.

In the final case illustrated we see that the autoaccelerator gap voltage changes sign in the middle of the pulse and that the x-ray output pulse is characterized by a rapid increase to a value considerably in excess of its initial amplitude. The x-ray output in the latter half of the pulse is also greater than that found in the case where the autoaccelerator gap was shorted indicating the increase in beam energy as a result of the autoacceleration process. A substantial change in the transmission line current is also evident. This current reaches a peak value of 9.5 kA, more than 50% greater than the injected beam current. The large value of the line current was determined by current doubling on reflection from the short circuit at the end of the line.

Figure 4 shows data obtained with different length transmission line sections. In the first case the round trip time on the line was reduced to 17 nsec and in the second case it was increased to 35 nsec. In both cases we show the autoaccelerator gap voltage and the x-ray yield from the electron beam hitting the thick target following autoacceleration. The change in pulse duration is apparent. In addition to the pulse duration changing, the effect of the pulse rise time compared to the transmission line round trip time is evident. Clearly for efficient autoacceleration it is necessary that the rise time of the pulse be short enough compared to the propagation time on the transmission line.

It is possible to describe the results obtained in terms of a simple transmission line model in which the primary beam energy is coupled to a lossless transmission line. The boundary condition at the beam is that of a current source. The effect of this is to produce a current pulse cancellation at the beam end of the line. This leads to a criterion for power flow from the line to the beam, namely that the current pulse, reflected from the short circuit at the end of the autoaccelerator line, exceeds 50% of the instantaneous beam current. This is seen experimentally as a reduction of the autoacceleration gap acceleration voltage with the short transmission line compared to that found in the longer line cases. The time taken to reverse the sign of the autoaccelerator gap voltage is greater than that predicted by the model. This is probably due to the frequency response of the ferrite. Inclusion of a 15 nsec rise time for the ferrite leads to waveforms approximately consistent with the experimental results. Figure 5 shows the output from the model for the 35 nsec transmission line. The curves shown represent the x-ray yield and the autoaccelerator gap voltage. These results have been obtained using the actual beam current and injection voltage waveforms and artificially increasing the round trip time to 50 nsec. A more detailed modeling including allowance

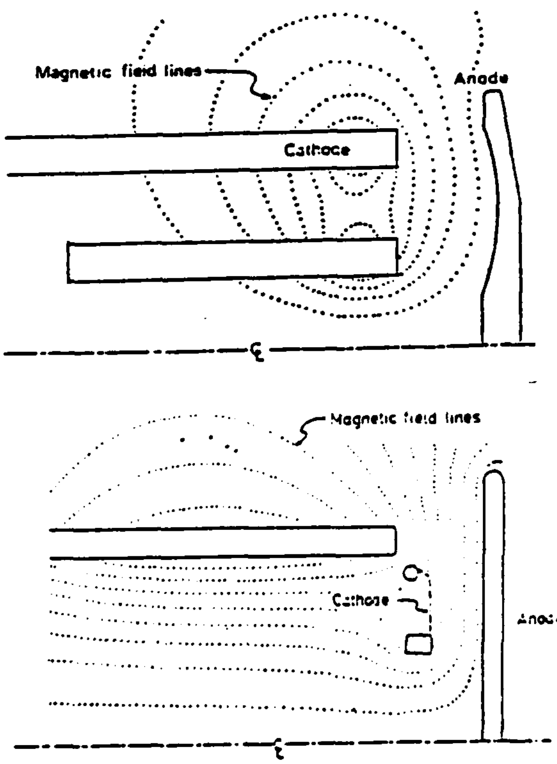

Fig. 1. Diode configurations used in proton inductive linac study.

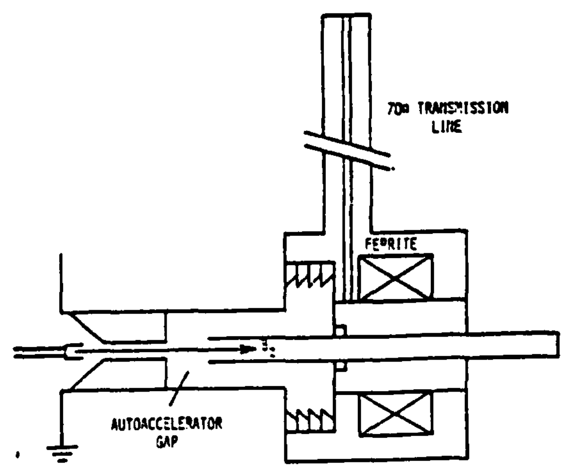

Fig. 2. Autoaccelerator schematic diagram.

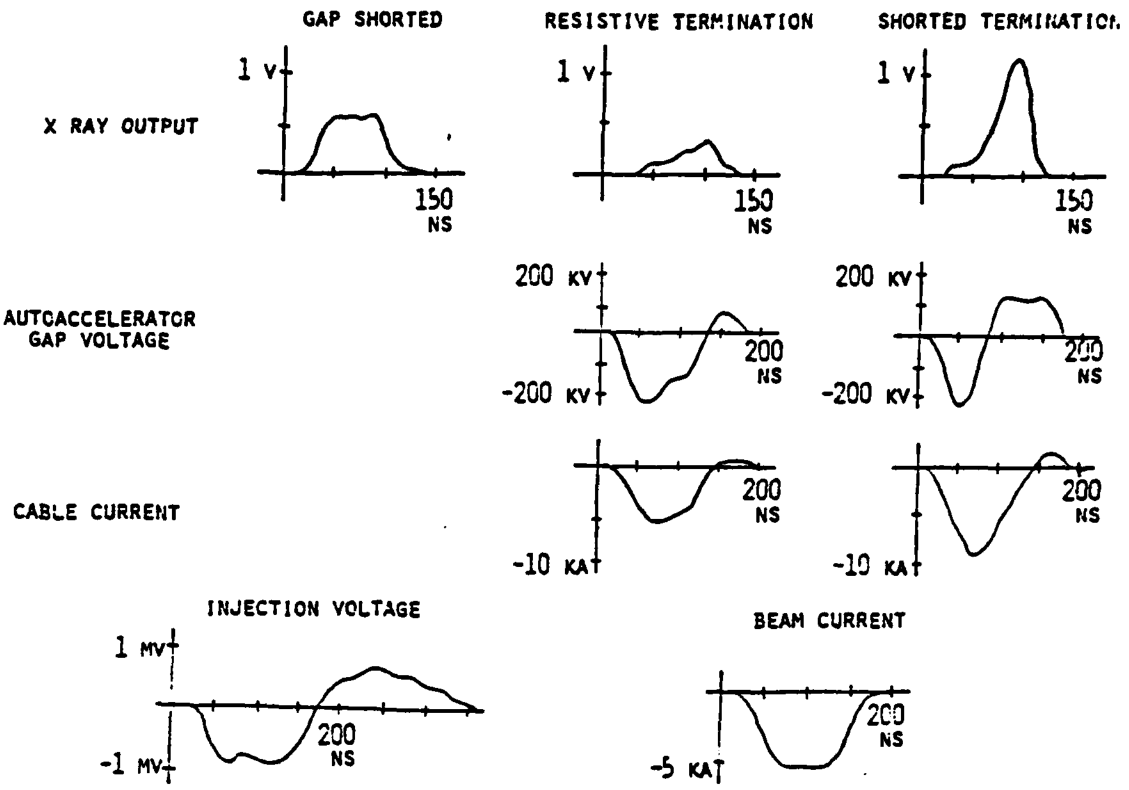

Fig. 3. Representative oscilloscope traces of autoaccelerator.

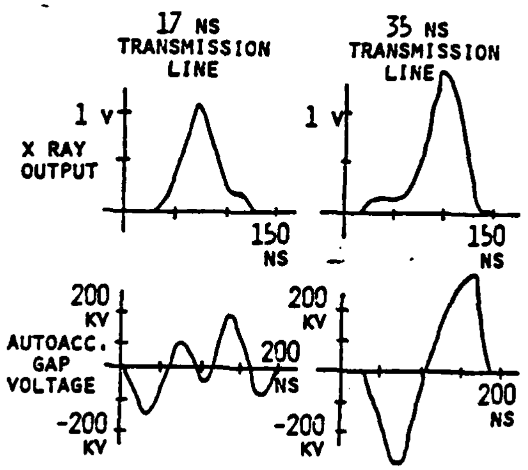

Fig. 4. The effect of transmission line length on x-rays and gap voltage.

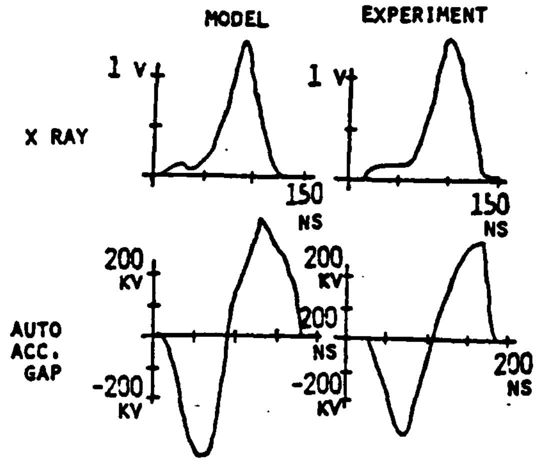

Fig. 5. Comparison of computed and experimental results.

of the transfer function of the ferrite transformer is in progress. The finite rise time effect of the ferrite cores will also reduce the computed output beam energy.

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